Improved Equivalent Circuit for Twin Slot Terahertz Receivers

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Abstract

Series-fed coplanar waveguide embedding circuits are being developed for terahertz mixers using, in particular, submicron-sized superconducting devices, such as hot electron bolometers as the nonlinear element. Although these mixers show promising performance, they usually also show a considerable downward shift in the center frequency, when compared with simulations obtained by using simplified models. This makes it very difficult to design low-noise mixers for a given THz frequency. This shift is principally caused by parasitics due to the extremely small details (in terms of wavelength) of the device, and by the electrical properties of the RF choke filter in the DC/IF line. In this paper, we present an improved equivalent network model of such mixer circuits which agrees with measured results at THz frequencies and we propose a new set of THz bolometric mixers that have been fabricated and are currently being tested.

1 Introduction

Slot antennas coupled to Coplanar Waveguides (CPW) are being developed for quasi-optical single-pixel detectors for atmospheric and astronomical instruments in the submillimeter-wave/terahertz-frequency range. Hot Electron Bolometer (HEB) mixers, for example, are often used at THz frequencies in such circuits placed at the second focus of a silicon lens. HEB receivers are currently being developed for frequencies up to 2 THz for the ESA/NASA Herschel Space Observatory, and up to 3 THz for NASA's SOFIA aircraft observatory. However, the measured center frequency of these mixers is often significantly lower than that calculated with simple models. As we show [1], the accurate characterization of the entire mixer embedding circuit, including the parasitics associated with the geometry of the device and the RF band stop filter used in the DC/IF line as well as the slot antennas and CPW-to-slot transitions, is needed to correctly design these THz mixer circuits. In this paper we present a procedure that characterizes the strong reactive contributions associated with the bolometer-to-CPW transition and with the RF band stop filter that connects the mixer to the DC/IF systems of the receiver. We first develop a method to calculate the characteristic impedance and the propagation constant of the coplanar waveguide, etched between two semi-infinite media (air and silicon), that connect the receiving slot antennas to the superconducting device. In particular, in the formulation we account for the power leakage due to radiation. We then describe the procedure to calculate the reactances due to the detailed geometry of the mixer device and circuit, and we correct the input impedance calculated with a commonly used simplified network. The agreement between the predictions obtained with our model and a complete set of measured data for seven mixers in the range between 500 GHz and 3 THz has been found execellent. Then, we analyze the features of our model and we present new designs for four different center frequencies (0.6, 1.6, 1.8 and 2.5 THz), required in several upcoming NASA and ESA missions.

2 Receiver Layout and Equivalent Network Parameters

The spectral response and hence the center frequency of HEB mixers with six different twin-slot antenna designs has been previously measured with a Fourier Transform Spectrometer (FTS) [2]. The antenna slot lengths ranged from 26 μm up to 152 μm. Fig. 1a shows a Scanning Electron Microscope (SEM) photograph of a 2 THz HEB mixer. The submicron-sized HEB device (i.e. "bolometer" in the figure) is connected to the twin slot antenna via a CPW transmission line [3]. On the right of Fig. 1a is the first element of an RF band stop filter structure. Fig. 1b shows a detail of the bolometer region and outlines the effect of the bolometer-to-CPW transition on the electric field and current. Fig. 2a defines the relevant parameters of the model while Fig. 2b shows the simplified equivalent network of the overall mixer embedding circuit. The active slot impedances Z_{sa} in the figure are obtained by means of MoM simulations restricted

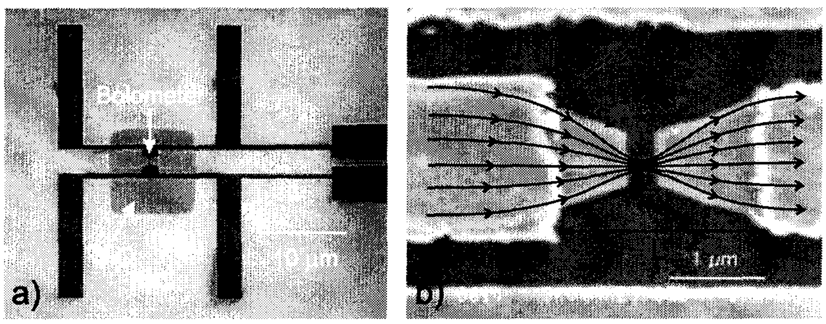


Figure 1: a) SEM photograph of a 2 THz HEB mixer embedding circuit. The superconducting bolometer is located at the center and coupled to the twin slot antenna via CPW lines. b) Bolometer detail with a schematic representation of the electric field lines (dashed) and of the RF current path (solid).

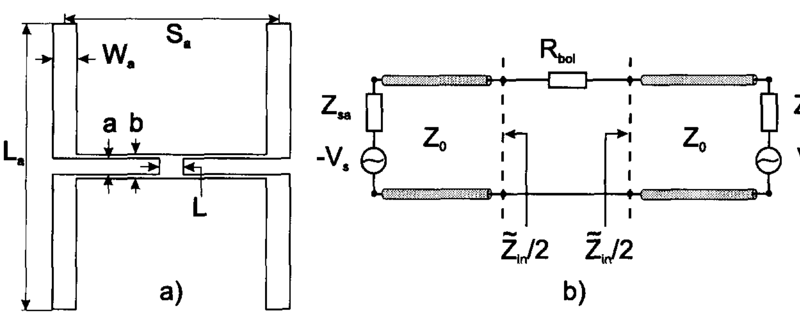
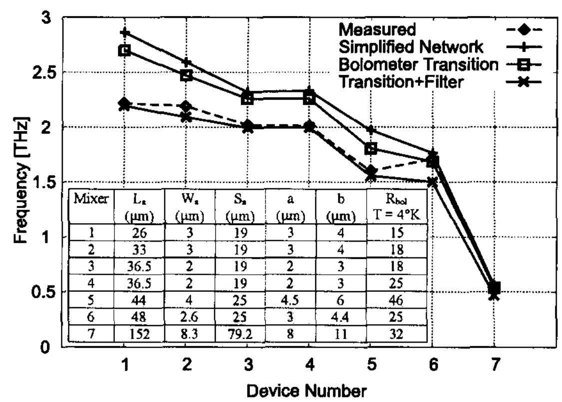


Figure 2: a) Schematic layout of physical structure used in the simulations with the relevant dimensions defined. b) Simplified equivalent network of the THz mixer circuit which includes the active slot impedance and the equivalent transmission lines.

to the receiving slots alone. R_{bol}, Z_0 and V_s represent the nominal bolometer DC resistance, the CPW characteristic impedance and the equivalent voltage source of the receiving antenna, respectively, while $\tilde{Z}_{in}$ is the equivalent input impedance seen by the bolometer in this simplified model. The parameters of the transmission line have been obtained using the formalism presented in [4] and applied in [1] to CPWs. The unknown magnetic currents are obtained from the direct solution of the pertinent Continuity of Magnetic Field Integral Equation (CMFIE) assuming, as in [5], the separability between transverse and longitudinal spatial dependence. In particular, the transverse electric field is assumed to be well represented by a unique edge singular function defined on each of the two slots composing the CPW. The procedure for finding the space domain magnetic current consists of: i) expanding via a Fourier Transform the transverse impressed magnetic field in spectral superposition of electric currents progressively phased by k_x; ii) finding in analytical form, for each k_x, the 2D Green's Function (GF) by imposing the continuity of the magnetic field at the slot axis; and iii) integrating in k_x all the 2D GF. Equating to zero the denominator of the spectral expression for the magnetic currents, a dispersion equation is obtained that, solved numerically, defines the propagation constant of the leaky mode supported by the structure. The definition of the characteristic impedance for a leaky line has been the subject of recent investigations; particularly promising is the one in [6]. In this paper we define the characteristic impedance as ratio between voltage and current of the leaky wave launched by a source at finite distance from the transverse section under investigation. This avoids some of the ambiguities associated with a leaky transmission line where the sources are assumed to be at infinite distance. The equivalent network, in Fig. 2b, alone does not account for the current crowding effect occurring in the bolometer region. Indeed, since the bolometer width is much less than the width of the CPW inner conductor, a strong reactive load is concentrated at this transition. Our analysis accounts for the effect of the transition, separately with respect to the remaining circuit, by combining two equivalent lumped reactances related to the length and width of the bolometer device (Fig. 1b). A detailed description of the analytical representation of these lumped reactances can be found in reference [1,4].

3 Numerical Results and Conclusions

Fig. 3 shows the center frequencies for the seven mixers under investigation. The parameters of the twin-slot mixers which have been fabricated and measured are given in the inset, along with the bolometer device DC resistance. In Fig. 2a the relevant geometric parameters are indicated. The measured results (dashed line with "prism" symbols) are compared with calculated curves that are obtained by using either the simplified network model as it is ("plus" symbols) or corrected via the reactive current crowding contributions ("square" symbols). These latter are obtained assuming a "staircase" shape for the flared transition between the bolometer and the inner conductor of the CPW, taking into account the actual dimensions of the mixer embedding circuits as measured with a SEM. The center frequency is even more strongly affected by the presence of the filtering structure. This latter has been modeled by simple transmission line theory, taking into account the radiation power leakage. Also shown in Fig. 3 are the results ("×" symbols) obtained when the impact of the RF filter is included. It is apparent that the agreement between prediction and measurements is outstanding, except for the case of mixer No. 6. These results give strong support to our improved equivalent network, considering the extreme challenges associated with fabrication and measurement at 2.5 THz and the fact that the modeling of the filter does not account for the "step" transitions between high and low impedance sections. In the past the observed shift has been attributed to unknown lumped reactive effects associated to the superconducting bolometer itself (i.e. thermal gradient and skin effect). The present analysis attributes the dominant part of the observed shift to the embedding circuit modeled in this paper. As a result of the present investigation it seems more convenient to operate the slot antennas on their first resonance (half instead of a full wavelength long slots). Indeed, even though the overall radiation pattern could be slightly affected and different from the theoretical optimum, the input impedance of the radiating slots turns out to be higher (about 140 Ohms for the real part of mixer No. 1 at 2.5 THz). In this way the slot input impedance is more stable and the impact of the imaginary part of the filtering structure is less significant because it is in series to a high impedance. Additionally, when the slot antennas are operated on their first resonance, the slot impedance presented to the bolometer via a $\lambda_{eff}/4$ long CPW transmission line is much lower and typically about 20 Ohms. This way a good match of the real part of this impedance with that of the bolometer is straightforward, which results in a nearly optimum efficiency. It is true that in this configuration the impact of the lumped reactances associated with the CPW-bolometer transition are more relevant. However, observing the analytical expressions of the impedances presented in [1], it is clear that the effect of this transition is much more negligible if the length of the transition L is reduced to the minimal realizable dimension without resorting to the flared transition of fig. 1b. Based on the previous con-



Mixer	L_s (μm)	W_s (μm)	S_s (μm)	a (μm)	b (μm)	R_{bol} T = 4°K
1	26	3	19	3	4	15
2	33	3	19	3	4	18
3	36.5	2	19	2	3	18
4	36.5	2	19	2	3	25
5	44	4	25	4.5	6	46
6	48	2.6	25	3	4.4	25
7	152	8.3	79.2	8	11	32

Figure 3: Summary of measured and calculated center frequencies for the seven mixers under analysis.

siderations and on the good results obtained, a new set of THz mixers has been fabricated and is currently being tested. Different designs at four center frequencies have been carried out; in particular we aimed at the following center frequencies: 0.6, 1.6, 1.8 and 2.5 THz. The bolometer has been fabricated in Niobium and the microbridge is always 0.1 μm wide, while the length has been chosen to be either 0.1 or 0.2 μm. Moreover, with this new set of mixers we designed two different transitions between the CPW inner conductor and the bolometer: a tapered one, like in the previous measured devices, and a new non-tapered one. The choice of a non-tapered transition has been suggested by the formulation presented in [1] and is expected to give a much more negligible lumped reactance in the equivalent circuit and therefore a smaller down shift in the resonating frequency. Finally, also the filter section has been re-designed accordingly.

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